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Long-term effects of topsoil removal on soil productivity factors, wheat yield and protein content

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Quantifying long-term effects of soil erosion on plant production and soil quality can aid in restoring degraded soils. The objectives of this study were to determine the long-term effects of topsoil removal on spring wheat (*Triticum aestivum* L.) yield and soil productivity factors. In 1982, the surface 0, 6, 12, and 18 cm of topsoil was mechanically removed from a Williams loam (fine-loamy, mixed, superactive, frigid Typic Argiustoll) and subsequently cropped. Soil samples were collected in 1998. There was no difference in soil organic matter (SOM), particulate organic matter (POM), mineralizable N, or water stable soil aggregates (WSA) in the surface 15 cm. Though not significant, there was an average increase of 1.2 g SOM kg^{-1} soil from the surface 15 cm since 1982, but fungal and bacterial biomass was reduced. The SOM and POM increased in the surface 15 cm of soil where grass was planted in strips between plots. Topsoil removal did not affect soil water at planting nor wheat yields from 1998–2001. The use of commercial fertilizer maintained crop yields, but SOM remained unchanged indicating that, restoring erosion damage is unlikely with a conventionally tilled wheat-fallow rotation in semi-arid regions.

Keywords: carbon pools; crop yields; erosion; long-term experiment; soil quality

Introduction

Loss of topsoil due to wind and water erosion has been a major concern of conservationists, economists, and producers for many decades. Erosion causes the loss or redistribution of soil carbon and plant nutrients with the loss of productivity and soil structure in the eroded portions of the field (Massee and Waggoner 1985; Mielke and Schepers 1986; Tanaka and Aase 1989; Tanaka 1990; Schumacher et al. 2005). However, yields have tended to increase in spite of continued erosive losses of topsoil. This yield increase has been attributed to technological advances such as improved plant cultivars, better cultural practices such as improved weed control, and the use of large quantities of commercial fertilizer (Krauss and Allmaras 1982). Often overlooked is the redistribution of topsoil from eroded hillsides to adjacent low lands and its effect on other soil quality and production parameters (Li and Lindstrom 2001; Papiernik et al. 2009). Massee and Waggoner (1985) found that production of wheat could not be restored on severely eroded soil with the addition

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of commercial fertilizers due partially to poor water retention, but largely to reduced water use efficiency. However, soils with topsoil deposition had increased water use-efficiency over that of non-eroded soil. Likewise, Mielke and Schepers (1986) found that the addition of topsoil to eroded hilltops increased plant dry matter production and grain yield of corn (*Zea maize*). Furthermore, the addition of fertilizer did not offset the yield loss in the absence of topsoil.

Restoring productivity to eroded semiarid soils is a slow process. Dormaar et al. (1986) found an artificially eroded soil in the Canadian Prairie was only partially restored after 22 years of cropping. The slow process of restoring degraded soils in semiarid regions is due in part to the practice of summer fallow and to the erratic and often-low levels of crop residues returned to the soil (Rasmussen et al. 1998).

Soil productivity restoration is often linked to various soil quality indicators such as soil organic matter (SOM), particulate organic matter (POM), water stable soil aggregates (WSA), mineralizable N, and microbial biomass. The SOM fraction changes slowly with management practices, but taken alone does not adequately account for changes in soil quality and nutrient status (Franzluebbers et al. 1995; Sainju et al. 2007). In contrast, mineralizable N and microbial biomass are considered active pools that change seasonally (Franzluebbers et al. 1995). The POM fraction is considered an intermediate pool for organic matter stability over time (Beare et al. 1994; Sainju et al. 2006). The WSA is generally regarded as a short- to intermediate-term indicator of soil quality and influences soil erosion potential, soil moisture status, nutrient dynamics, compaction, and plays a role in regulating water movement into and through the soil profile (Kemper and Rosenau 1986; Whalen et al. 2003).

The objective of this study was to compare various soil and crop parameters (SOM, POM, WSA, bacterial and fungal biomass, mineralizable N, wheat yields and grain protein) among four levels of topsoil removal after 16 years of conventional wheat-fallow management in the semiarid northern Great Plains. Soil parameters were also compared with grass strips that were planted between plots when the site was established.

Materials and methods

Plots of this study were established in 1982 on a Williams loam 11 km northwest of Sidney, MT (47°46′ N, 104°15′ W). Soil was mechanically removed with a small paddle scraper to 0, 6, 12, and 18 cm depths corresponding to no removal, half the Ap horizon, all of the Ap, and all of the Ap and half the B21t horizon, respectively (Tanaka and Aase 1989). Initially, the statistical design was a split-plot with soil removal treatments as main plots and fertilizer additions (various combinations of N and P, Tanaka and Aase 1989) as subplots. Soil removal plots were arranged as a randomized complete block design and measured 15 × 48 m with a 2 m wide grass buffer planted between plots in each block and a 15 m grass alleyway between blocks. These areas were planted with creeping red fescue (*Festuca rubra* L.). Vehicle traffic over the buffer strips was kept to a minimum. Three replications each of hard red spring wheat (*Triticum aestivum*) and summer fallow were present each year, and alternated in succeeding years (1982 through 1990). Fallow tillage used sweeps at a depth of about 0.1 m in late May followed by two or three operations with a rod weeder as needed for weed control.

Fertilizer subplots were discontinued in 1989 when main plots received uniform applications of N as ammonium nitrate (34-0-0, 35 kg N ha^{-1}) and P as mono-ammonium phosphate (11-52-0, 26 kg P ha^{-1}) prior to planting each year. From 1991–1999 all plots were managed the same as either fallow (F) or spring wheat (W) in the order W-F-W-W-F-W-F-W-W. In 2000, peas replaced wheat in one-half the plots establishing a wheat-pea rotation to break weed and disease cycles. With the shift to annual cropping and a history of low grain protein for all soil removal treatments, the N rate was increased to 56 kg N ha^{-1} as urea (45-0-0) and 6 kg N ha^{-1} in 11-52-0 for a total of 62 kg N ha^{-1} to match the N removed by an average crop (Cook and Veseth 1991). The P rates were almost three times the amount removed and were not changed.

Soil physical and chemical analysis

In mid-May 1998, two soil cores (5-cm i.d.) from each plot and the six grass barrier strips were obtained in 6 cm increments to a depth of 36 cm and composited by depth. The soil was weighed and air-dried. Sub-samples were dried at 105°C to adjust air-dried weights to oven dry weight for the determination of soil profile water content and soil chemical and physical analysis. Soil bulk density was measured for each depth based on the sample volume and oven dry soil weight. Soil pH was determined in a soil:water ratio of 1:1 with 15 g soil in distilled water.

Total soil aggregates were determined by placing the equivalent of 20 g oven dry soil on a shaker with a 2.0 mm and 0.6 mm nest of sieves. Material larger than 2 mm was discarded and the soil aggregates remaining on the 0.6 mm sieve were weighed and recorded as total aggregates. Four g of aggregates were used to determine water stable aggregates using the method described by Kemper and Rosenau (1986). The SOM and POM were determined on a separate set of soil samples, taken in the same manner described previously but to a depth of 0–15 and 15–30 cm, by using 10 g (SOM) and 30 g (POM) soil by weight loss on ignition at 360 °C for 2 h (Cambardella et al. 2001). This temperature was chosen to avoid C loss associated with soil carbonates (Tiessen and Moir 1993). Samples for POM analysis were first prepared by adding 90 ml of 5 g l^{-1} sodium hexametaphosphate, dispersing for 16 h, and passing the solution through 0.5 and 0.05 mm nested sieves.

Biological analysis

A separate set of soil samples were obtained at 0–6 and 6–12 cm depth from the plots and grass buffers for determination of microbial biomass and mineralizable N. These samples were kept field moist and refrigerated at 4°C until processed within 24 h. Mineralizable N was determined by a modification to the procedure described by Stanford and Smith (1972) (Sparrow and Cochran 1988). The equivalent of 50 g dry soil was placed in a filter funnel with a 0.22 μm membrane, 50 ml of N free nutrient solution (Stanford and Smith 1972) was added and let stand for 1 h, after which 0.01 MPa suction applied overnight (about 16 h) to remove free water. The extract was then frozen and stored at -15°C until thawed and immediately analyzed for nitrate-N and ammonium-N by continuous flow auto-analysis using a Lachat Quick Chem 8000 Automated Ion Analyzer. The wetting and extraction procedure was repeated at two-week intervals for 12 weeks. The amount of mineralizable N was based on the cumulative mineral N from weeks 2 through 12 for each soil removal

treatment and the grass buffers. The mineral N in the first extraction was not included as mineralizable N because it represented N in the soil at the time of sampling. Values were expressed volumetrically using field-based soil bulk density.

Microbial biomass was determined on soils from each treatment at 0–6 and 6–12 cm depth increments. Soil samples were processed within 24 h after field collection. Soil samples were treated using the technique of Frey et al. (1999), except soils were fixed with paraformaldehyde (final concentration 3%) before being smeared onto microscope slides for staining. Bacteria and fungi were stained with DTAF (5-(4, 6-dichlorotriazin-2-yl) amino fluorescein) (Bloem et al. 1995). A Zeiss LSM 410 confocal laser scanning microscope fitted with an argon laser and connected with a Zeiss Axiovert inverted microscope was used to detect bacteria and fungi in soil smears. Excitation was 488 nm and fluorescence was detected at 520 nm. Observations were made with a C-Apochromat 63 × 1.2 N water immersion and a Plan-Apochromat 100 × 1.4 NA oil immersion objective lens. From each of 10 different areas of each slide, nine optical images (0.5 μm thick) were captured and compressed in one final image of 128 × 128 μm (1024 × 1024 pixels) with all bacteria and fungi from the total 4.5 μm-thick smear layer. Fully automated Zeiss KS400 image analysis software was used to count the number of bacteria and measure fungal length. Bacterial biovolumes per cell were calculated according to Bloem et al. (1995). To measure biomass in soil, the conversion factor of 1.3×10^{-13} g C μm^{-3} for specific bacterial C content was used (Bloem et al. 1995). A conversion factor of 0.33×10^{-12} g C μm^{-3} for determining biomass from biovolume was used for fungi (van Veen and Paul 1979).

Grain yields and protein content

Grain yield was determined by harvesting a 1.5 m wide strip from the length of the plots with a plot combine in 1998–2001. Yields were adjusted to the equivalent of 13% moisture content. Protein was determined by near infrared analysis using a Brann-Luebbe InfraAlyzer calibrated for whole grain (Personal communication, Dr Charles Flynn, Montana State University, Eastern Agricultural Research Center, Sidney, MT 2001).

Statistical analysis

An analysis of variance (SAS Inst. 2007) was completed on all soil and crop data using a randomized complete block design. Comparison of soil parameters was run independently for each soil depth using LSD ($p \leq 0.05$) as the mean separation technique. Yield and protein content were analyzed separately for each year because of changes in management practices.

Results and discussion

The grass borders had significantly greater SOM and POM than the control (no topsoil removed) (Table 1). There was no difference in SOM or POM in the top 15 cm of soil due to topsoil removal, and there was significantly lower SOM only with the removal of 18 cm topsoil. There was less POM with the removal of 12 and 18 cm of topsoil than with the removal of either 0 or 6 cm of topsoil. Comparing the SOM values with that of archived samples taken immediately after topsoil removal

Table 1. Soil organic matter (SOM) and particulate organic matter (POM) 16 years after removing 0, 6, 12, and 18 cm of topsoil, and for an adjacent grass border planted at the time of topsoil removal.

Treatment	SOM 0–15 cm	SOM 15–30 cm	POM 0–15 cm	POM 15–30 cm
	---------- g kg^{-1} soil----------		---------- % of SOM ----------	
Grass	40.4	34.2	30.1	18.0
0 cm	33.8	30.8	18.1	14.0
6 cm	33.4	31.7	17.7	9.7
12 cm	34.2	31.8	13.4	9.5
18 cm	33.4	29.4	14.6	9.2
$LSD_{(0.05)}$	1.1	1.1	4.8	2.8

in 1982 showed that all topsoil removal treatments increased an average of 1.2 g SOM kg^{-1} soil in the top 15 cm of soil with no difference due to amount of topsoil removed (data not shown). Thus, all soil removal treatments continued to at least maintain existing levels of SOC following topsoil removed.

Since 1982 there was an increase of 2.5 g SOM kg^{-1} soil in the top 15 cm of the grass borders compared to the control, but there was no increase in SOM at the 15–30 cm depth. This is consistent with other studies. For instance, Reeder et al. (1998) found that six years after establishing grass on a clay loam that had been tilled and cropped for 60 years, soil organic C increased in the surface 2.5 cm depth only. In a multi-site study throughout the Great Plains, Gebhart et al. (1994) found fields planted to mixed grasses for five years under the Conservation Reserve Program had C increases only in the top few cm of soil. Furthermore, Reeder and Schuman (2002) found grazing native range increased soil organic C in comparison to that in exclosures. They attributed this to greater deposition of plant material on the soil surface and reduced root proliferation in the absence of grazing. The grass strips between our plots were never grazed or mowed, thus C storage was likely less than the maximum potential for this area.

Mineralizable N was quite variable with no difference among treatments and ranged from 0.8–6.2 mg kg^{-1}. This lack of difference due to soil removal is consistent with the uniform levels of SOM from all treatments. El-Harris et al. (1983) found fertilizer N rates affected N mineralization potential in a wheat-fallow rotation. These plots received the same rate of N fertilizer and had similar yields since 1989. Therefore, the amount and quality of crop residue returned to the soil would be the same, which would support similar microbial activity (Reinertsen et al. 1984; Cochran et al. 1988).

Bacterial biomass in the top 6 cm of soil was unaffected by removing 6 cm of topsoil or planting grass. However, there was a significant decrease in bacterial biomass with the removal of 12 and 18 cm of topsoil (Figure 1a). At the 6–12 cm depth, there was no affect of planting grass or topsoil removal on bacterial biomass. There was an increase in fungal biomass in the surface 6 cm of soil with grass as compared to the cropped control, but it was not significant (Figure 1b); however, there was a significant decrease in fungal biomass with the removal of 6, 12, or 18 cm of topsoil. At the 6–12 cm depth, there was a significant increase in fungal biomass with planting grass and no affect of topsoil removal.

The lack of difference in SOM levels over time among topsoil removal treatments suggests similar long-term microbial activity. It is possible the old SOM at the deeper

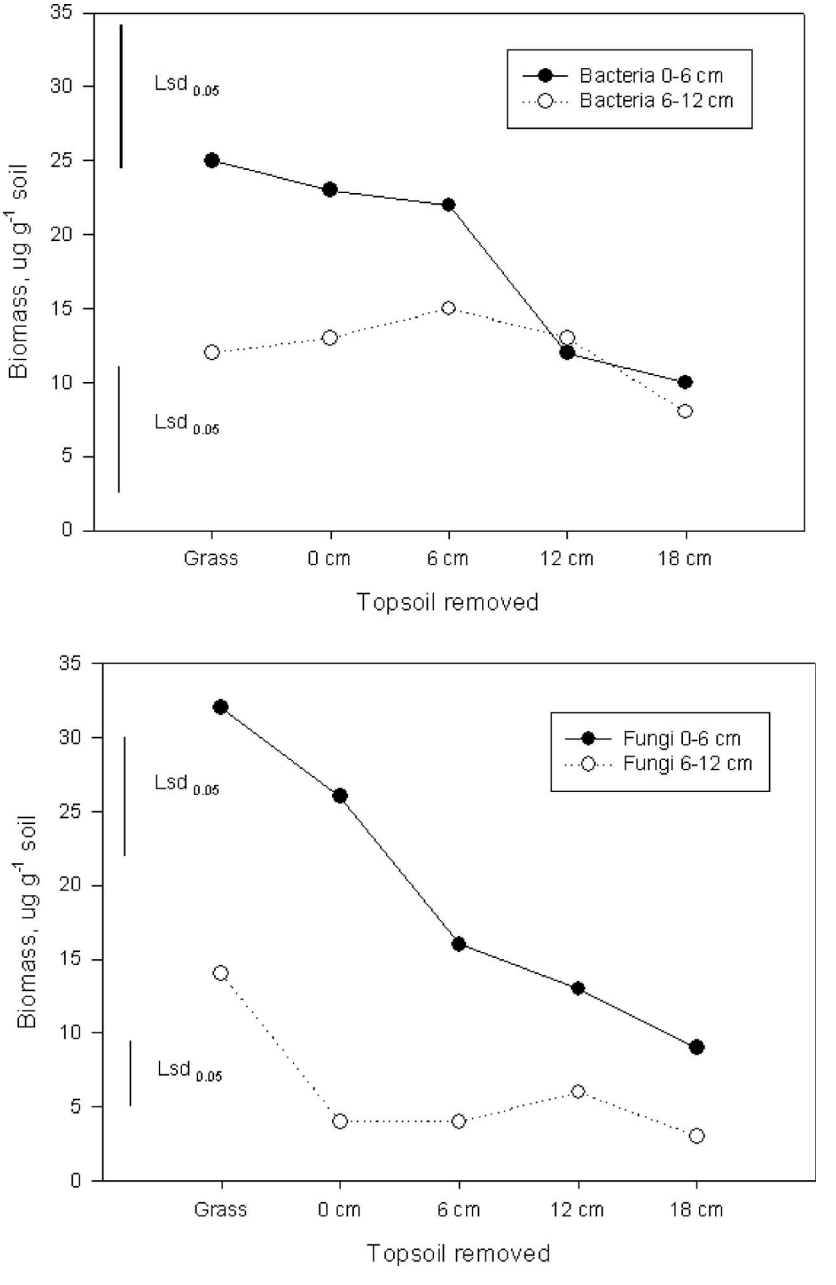

Figure 1. Effect of topsoil removal on bacterial (a) and fungal (b) biomass including adjacent grass border strips as a reference.

depths is more recalcitrant than that removed and thus does not support a microbial population as high as that originally nearer the surface. However, total C returned to the soil influences SOM dynamics (El-Harris et al. 1983). Yields were lower from plots with topsoil removed during the first few years of the study (Tanaka and Aase 1989). Also, because yields were not determined between 1990 and 1997, it is possible

total C returned to the plots with topsoil removed was substantially less than the control. The possibility of lower production prior to 1998 could account for less microbial biomass and no difference in the levels of SOM (i.e. less C returned to the soil supported less microbial activity where more topsoil was removed).

Water stable soil aggregates (WSA) were not affected by the removal of topsoil (in 1982) or perennial grass after 16 years (Table 2). This is surprising because the grass borders had almost 20% more SOM and almost twice as much POM in the top 15 cm of soil than the cropped plots with or without topsoil removal. Both of these soil measurements have been positively associated with the formation of WSA (Bird et al. 2002; Chan et al. 2002). We are not aware of any management practices that would have prevented formation of WSA in these strips. Vehicular traffic across the grass strips was minimal, with most field activities (tillage, planting, harvesting, etc.) parallel to but outside the grass borders. Water stable aggregates increased with depth, which we attribute to less soil disturbance below the tillage depth and to slightly greater soil clay content (Tanaka and Aase 1989).

Soil pH values were higher where 18 cm of topsoil was removed in the top 12 cm of soil than the control. Soil pH values were also higher than the control for the 12–24 cm depth with 18 cm of topsoil removed and with all topsoil removal treatments at the 24–30 cm depth (Table 3). Comparing the current values to that at their original depths indicates there has not been a change in soil pH over the 16 years since the topsoil was removed. Evidently, the use of acid forming fertilizers has not been sufficient to overcome the buffering capacity of this soil, which contains carbonates below 18 cm.

There were no differences in over-winter storage of water in the soil profile, grain yield, or grain protein due to topsoil removal in 1998 (Table 4). The 1998 crop followed summer fallow, which may have masked water or nutrient stresses. Therefore, spring wheat was planted in place of fallow for the 1999 and 2000 crops. In 1999, stored soil water at planting was similar to that in 1998, but grain yields and grain protein were lower than the previous year due largely to below normal precipitation during the growing season. There was a trend of lower grain yield with topsoil removal but it was not significant; however, grain protein was lower with the removal of topsoil indicating inadequate available N. Precipitation was below normal in the fall of 1999, which carried over to lower soil water contents at planting in 2000. Plots with 18 cm of topsoil removed had the most soil water, which we attributed to less water extraction by the previous crop because of low grain yield in

Table 2. Effect of grass and 0, 6, 12, and 18 cm of topsoil removal on water stable soil aggregates.

	Topsoil removed					
Depth cm	Grass	0 cm	6 cm	12 cm	18 cm	$LSD_{(0.05)}$
	g aggregate kg^{-1} soil					
0–6	190	220	280	260	250	NS
6–12	230	260	330	300	320	NS
12–18	300	320	350	320	310	NS
18–24	320	320	330	300	300	NS
24–30	330	320	330	350	300	NS
30–36	320	330	300	310	300	NS

Table 3. Effect of grass and 0, 6, 12, and 18 cm of topsoil removal on soil pH.

Depth cm	Topsoil removed					
	Grass	0 cm	6 cm	12 cm	18 cm	$LSD_{(0.05)}$
	pH					
0–6	7.22	6.71	6.82	7.27	7.51	0.71
6–12	7.50	6.98	6.98	7.35	7.73	0.68
12–18	7.15	6.95	7.42	7.56	8.08	0.52
18–24	7.57	7.33	7.63	7.93	8.27	0.42
24–30	7.79	7.68	7.92	8.03	8.18	0.21
30–36	7.91	8.25	8.27	8.24	8.44	NS

Table 4. Effect of soil removal on spring soil water (0–120 cm), spring wheat grain yield, and grain protein.

Topsoil removed cm	Soil water cm	Grain yield kg ha^{-1}	Grain protein %
1998 (After fallow)			
0	24	2290	11.5
6	24	2350	11.2
12	25	2050	11.1
18	24	2120	11.1
$LSD_{(0.05)}$	NS	NS	NS
1999 (After wheat)			
0	24	1330	9.8
6	23	1470	9.4
12	25	1180	8.9
18	26	1170	8.7
$LSD_{(0.05)}$	NS	NS	0.9
2000 (After wheat)			
0	18	1350	11.3
6	18	1270	9.3
12	19	1320	9.3
18	21	1400	10.0
$LSD_{(0.05)}$	2	NS	NS
2001 (After peas)			
0	29	2980	11.3
6	29	2970	11.5
12	32	2900	12.1
18	31	2920	12.6
$LSD_{(0.05)}$	NS	NS	NS

1999. In 2000, grain yields were comparable to those in 1999 due to spring rains offsetting the reduced stored soil water. Grain protein was slightly higher than 1999 and not affected by the removal of topsoil. In 2001, greater than average fall precipitation and rain in June and July contributed to higher grain yields and protein compared to the two previous years. There was no effect of topsoil removal. The higher protein levels in 2001 compared to the previous two years along with increased yields indicates greater N uptake. This is likely due to both greater availability of N from the pea straw and to timely rains contributing to more favorable soil water for N mineralization (Rasmussen et al. 1998).

Average pea yields (1500 kg ha^{-1} in 2000 and 2000 kg ha^{-1} in 2001) were not affected by topsoil removal. In general, the wheat and pea yields are comparable to those achieved by growers in this area. However, our protein levels were considerably below the targeted level of 140 g N kg^{-1} for hard red spring wheat. Engel et al. (1999) found that the critical protein level for hard red spring wheat was 130 g N kg^{-1}. Below 130 g N kg^{-1}, additional N increased grain yields, while above this level, additional N resulted in greater grain protein. We found in years with the best grain yields, grain protein was also higher even though we applied the same amount of N each year. The low protein contents during years with low yield may have been caused by insufficient spring and summer rainfall to move the applied N to sufficient depth for uptake during head fill. Cochran et al. (1978) and Smika and Grabouski (1976) found having the bulk of the N at the same depth of greatest water extraction by wheat during head fill increased grain yield and protein content.

Conclusion

Although erosion or mechanically removing topsoil can substantially reduce soil organic matter, organic N and microbial biomass, our measurements of WSA, SOM, and POM in the top 15 cm of soil were not significantly different 16 years after artificial topsoil removal. Tanaka and Aase (1989) found that reduced productivity initially following topsoil removal was related more to P fertility than N, but that addition of mineral N and P fertilizer did not fully overcome the apparent reduced yield potential. However, continued application of P over that removed by the crop at all depths of soil removed appears to have overcome the soil P deficiency as evidenced by the much higher than normal yields for this area in 2001 with no difference due to topsoil removal. Protein was only affected by topsoil removal when we eliminated fallow and recropped after wheat, which created additional N stress. Differences in soil profile water content were not adversely affected by topsoil removal and differences in grain yields were not evident. Because this site is nearly level, water runoff did not occur, except in extreme events. Also, it was unlikely the slight change in soil texture within the rooting depth of spring wheat adversely affected water infiltration or root proliferation. Thus, infiltration was likely unaffected by topsoil removal, and the only time there was a significant difference in spring profile water content, the treatment with the greatest topsoil removal had the most water. Therefore, yields could be maintained by applying commercial fertilizer to supply the mineral nutrition required by the crops.

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